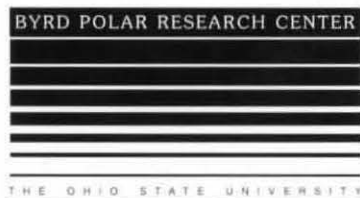
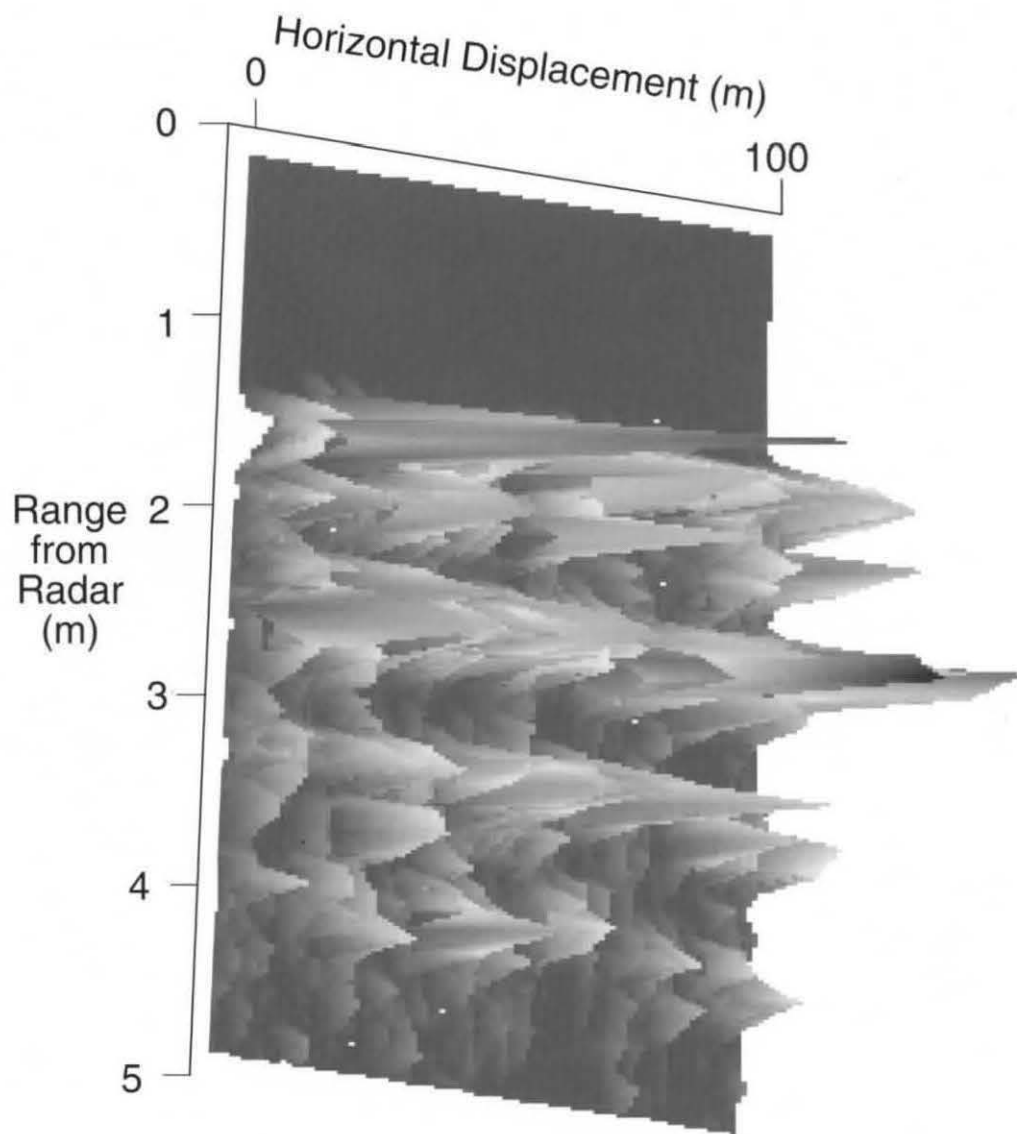


Radar and Snow Structure Studies in the Percolation Zone of the Greenland Ice Sheet:

A Data Report on the 1993 Field Season at Dye-2



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**Radar and Snow Structure Studies in the Percolation
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1 Introduction

From June 18 to July 12, 1993, a Byrd Polar Research Center (BPRC) team undertook radar and snow physical properties studies near Dye-2, in the percolation zone of Greenland's ice sheet. These studies were intended to advance our understanding of the microwave scattering properties of the ice sheet, in order to better interpret satellite remote sensing signals for mass balance and climate studies. This report summarizes the experiments performed and the data collected. Table I summarizes a list of our measurement objectives.

The Dye-2 team consisted of Ingrid Zabel, Paul Baggeroer, and Henry Brecher (from BPRC). We worked in close cooperation with other researchers performing separate experiments at Dye-2, namely Mark Anderson and Clint Rowe from the University of Nebraska, and Ellen Ferraro from the University of Massachusetts. At the same time a second team consisting of Kenneth Jezek (BPRC), Robert Thomas (NASA), and Karl Kuivinen (Univ. of Nebraska) carried out a surface traverse from approximately 70° N to 65° along roughly the 46th meridian West.

In general terms, our work at Dye-2 consisted of making radar observations of the snow at Ku-band (13.5 GHz) and a variety of incidence angles. The radar frequency is the same as that of the radar altimeter aboard the ERS-1 satellite. In conjunction with the radar observations, we dug pits in the snow and recorded physical properties such as snow stratigraphy, density, and grain sizes. In section 2 we present a map of the camp and experiment sites. In sections 3 and 4 we describe the pit and radar studies in detail. Finally, section 5 is a detailed chronology of the field season.

2 Site Map

Figure 1 is a regional map showing the traverse route, snow pits along the route, and Dye-2. Pits along the traverse route were sampled for temperature, grain size, and stratigraphy. A more detailed examination occurred at the most northerly spoke of the strain hexagon located at about 65° N. There, along with temperature, grain size, and stratigraphy, density data from pit walls and from an 11 m core hole were collected. Figure 2 shows the major features of the experimental site near Dye-2. Near the camp is a track-

free zone where the snow was initially left undisturbed for radar studies. Eventually we dug pits in this zone at the spots where we acquired radar data.

Outside of the track free zone are other pits which we sampled. Pits 1-5 were approximately 2 m deep. The sites of the deep pits 1-5 were chosen to match the flight line of a NASA P-3 aircraft, which flew overhead several times while operating various microwave and optical sensors. The locations of the shallower (1 m) pits were chosen to probe interesting regions, or to update the near-surface stratigraphy near one of the deeper pits. This updating was necessary in cases where we took radar measurements near a deep pit several days after it had originally been dug and sampled. Weather-related changes (e.g., snowfall, melting) could alter the stratigraphy, requiring us to dig new shallow pits for the most current information.

We recorded temperatures down to 2 m depth with a probe which was stationed near pit 1 from June 21 to June 29. On the 29th we moved the probe to the northwestern corner of the track-free zone, where it remained until July 9. We recorded the temperature at 10 m depth with a thermistor string dropped down a hole drilled by the Nebraska team in Pit 4.

3 Dye-2 Pit Studies

We attempted to document as fully as possible the snow probed by the radar. To do this, we dug pits underneath areas where the radar had been active, or, conversely, we made radar measurements near existing pits. Two of the deep pits were backlit, that is, we dug an additional pit close to an existing pit, covered the original pit, and were able to observe the snow stratigraphy from within the covered pit due to illumination through the snow wall connecting the two adjacent pits. Figure 3 shows some of the types of data we acquired.

We have documented stratigraphies of 14 pit walls of varying depths. These records consist of written descriptions of the general snow types encountered (e.g., "fine-grained" or "hard-packed") as a function of depth, together with drawings and some photographs. Figure 4 shows an approximately 1 m section of a backlit pit wall. During the early part of our field season we saw horizontal layers of snow and ice, but no localized ice structures. As time went on and surface melting occurred, however, we observed the formation of small ice pipes and ice lenses. An ice layer at a depth of

about 1 m was a ubiquitous feature of the snow at Dye-2: we observed this layer in every pit.

In addition, we have descriptions of approximate grain size and shape vs. depth from 8 pit walls. These are the result of observation with a magnifying glass which had a millimeter scale etched into the base (a "linen tester"). We also have photographs of snow grains extracted at various depths from Pit 2. Finally, we acquired 8 snow samples by saturating small boxes of snow with dimethyl phthalate, a chemical which solidifies in the pore spaces of the snow, creating a mask of the snow structure if kept frozen but exposed to air so that the snow can sublimate away. We returned with these samples to the Byrd Polar Research Center, where they await to be thin-sectioned and photographed.

We have snow density data from 8 pits. These data were acquired by weighing contents of a tube of known volume which had been driven into the snow. We also sampled densities of several extremely-hard packed or icy layers by cutting out pieces, measuring their dimensions, and weighing them. Some of our density data we acquired ourselves; the remainder was acquired by the University of Nebraska group. We also have snow wetness versus depth data for 4 pit walls, courtesy of Ellen Ferraro. She made these measurements with a conductance gauge; the snow wetness can be extracted from measurements of the real part of the snow dielectric constant (cf. Fig. 3). We do not have wetness data taken at the same time as our radar observations. We do, however, have concurrent snow temperature data which we can hopefully use to estimate the wetness when necessary.

Finally, in several pits we extracted ice lenses and recorded their surface roughness with a comb gauge. In a deep pit in the track-free zone and in pit 1 we recorded surface roughness of the ice layer at about 1 m depth. We also have several measurements of the snow surface roughness near areas where radar data was acquired. These measurements were made with a large scale comb gauge. We have photos and/or drawn traces of the comb gauge measurements, as well as photos of the rough surfaces.

4 Radar Studies

We performed three types of radar experiments and two types of calibration tests at Dye-2. Before describing these, brief mention should be made of

difficulties we experienced during the 1993 field season, for future reference.

Our radar was constructed at Ohio State by University of Kansas Professor S. P. Gogineni while on sabbatical. It was tested at Ohio State and in Søndre Strømfjord, Greenland, and was found to have occasional problems related to triggering, but was running well. Once in the field, however, we found that the instrument was very sensitive to line voltage. When voltage exceeded about 113 volts, the data acquisition system locked.

Two additional problems we encountered were i) the computer system we used did not always save all the data being acquired, and ii) range calibration with the Luneberg lens was difficult. On several occasions the digital triggering mechanism of the radar broke down and the returns are difficult to interpret. The majority of data collected, however, are of high quality.

We made stationary measurements of the snow from incidence angles of 0° to $\sim 60^\circ$. The radar was mounted on a sled (see Figure 5) which also held a generator. Electronic and computer equipment in support of the radar were kept either on the sled or nearby in a small tent. At 0° the range from the radar to the snow surface was typically around 5 feet.

We conducted these measurements at several spots in the track-free zone, as well as at Pits 1-5. At pits 1-3 we took radar measurements after the pits had been dug, several meters away from the pit. At pits 4,5, and "A-B" we first took the radar measurements, and then dug the pit directly below the observation area. Sometimes we would make measurements at several spots and at many angles once during the morning and once during the evening; at other times we would take data at fewer angles but more often throughout the day. Our choice of schedule was driven by weather-dependent effects we wanted to observe, or by time limitations due to other work (such as pit studies) which we wanted to accomplish.

On two relatively warm and sunny days where we suspected melting was occurring, we illuminated the snow surface, then dug down and leveled off an area in front of the radar in order to probe a drier layer. For the majority of our radar measurements we have accompanying air and snow surface temperatures, to help us estimate the degree of melting.

We also performed a transmission experiment on a relatively cold and overcast day. This experiment consisted of digging a lateral cave at the bottom of an existing 2-meter pit, placing the Luneberg lens in the cave, and taking radar measurements at 0° in order to recover the transmission characteristics of the snow. We then dug another cave about a meter higher,

just above an ice layer, and repeated the measurement with the Luneberg lens in this cave.

The last type of radar experiment we conducted was a traverse. This was done in order to get the scattering characteristics of the snow along a linear profile and thus to recover a map of snow stratigraphy. We pulled the sled with the radar along a 100 m transect, stopping every meter to make a measurement at 0° incidence. This transect ran approximately North-South, about 700 m west of the camp. In addition, we took data along a 600 m transect, traveling in from the site of the 100 m transect towards Pit 4, stopping every 50 m.

We performed two types of calibrations: range calibration measurements with a Luneberg lens, and a recording of the antenna pattern from scattering off of a flat metal plate. We did extensive range calibrations with the Luneberg lens on the first and third week of the field season, and in addition we made two calibration measurements with the lens before each radar experiment during the last week.

5 Chronology

June 18 Arrive at Dye-2 ~ 5 P.M.; begin camp set-up.

June 19 Storm all day.

June 20 Storm lasts through mid-morning. Continue camp set-up. Mark out location of track-free zone. Midday: light snow.

June 21 Set up and test radar. Not functioning. Pit 1 dug. Set up 2-m temperature probe by Pit 1. 10 A.M.: $T = -13^\circ \text{C}$.

June 22 Work on radar. Still not functioning. Find it works with Nebraska group's generator. Warm and wet. 8 A.M., $T = -8^\circ \text{C}$. 3 P.M.: $T = 0.1^\circ \text{C}$. Get GPS locations of tents, Pit 1.

June 23 Measure ice layer roughness in Pit 1. Radar range calibration done outdoors. Take angle of incidence data at one spot in track-free zone.

June 24 Radar measurements at spots in track-free zone. Small pit near one spot. Measure snow surface roughness with large comb gauge.

Evening: more radar spots in track-free zone. Find ice pipes near surface in shallow pit behind radar. Pit 2 dug.

June 25 Radar samples every hour from 9 A.M. to 5 P.M. in track-free zone. Continue sampling nearby shallow pits. Snowfall in evening.

June 26 Several inches of snow fell previous night. Radar spots in track-free zone. 2:30 P.M.: $T = -3^{\circ} \text{C}$.

June 27 Dig second pit by Pit 2, for backlighting. Pit 3 dug. Sample Pit 3 (stratigraphy, grain sizes, density, etc.). 5 P.M.: $T = -2.7^{\circ} \text{C}$.

June 28 Sample Pit 2, photograph grains. Radar at Pit 3. Dig out top surface and repeat radar measurements. Radar at Pit 1. 10 P.M.: fog rolls in from North.

June 29 Light snow. Move 2 m temperature probe from near Pit 1 to NW corner of track-free zone. Attempt to record 10 m temperature in pit 3. Dig Pit "A-B" in track-free zone (below sites of radar spots "A" and "B"). Sample Pit "A-B".

June 30 Moderate-heavy snow. Radar sample at future site of Pit 4. Pit 4 dug.

July 1 Several inches of snowfall from yesterday. Radar at Pit 2. Remove surface snow layer and repeat radar measurements. Traverse party from Crawford Point arrives. Dig and sample additional pit near Pit 2. Stratigraphy in Pit 4. 10 P.M.: $T = -11^{\circ} \text{C}$.

July 2 Light snow. Work on Bernoulli drive, backing up data. Calibrate radar at 0° , 25° . 8:20 P.M.: $T = -3.6^{\circ} \text{C}$.

July 3 Snow samples taken at small pit in track-free zone. Backlight Pit 4. 10 m temperatures in Pit 4, probe left overnight.

July 4 Storm.

July 5 Remove 10 m temperature probe from Pit D. Radar transmission experiment at Pit 4. Light-moderate snow all day.

- July 6** Radar at site of Pit 5. Problems with digital trigger. Pit 5 dug. Record radar antenna pattern with flat metal plate experiment. Begin extensive range calibration.
- July 7** Fog in morning. Continue range calibration. Sample Pit 5. Take snow structure samples. 9 P.M., $T = -4^{\circ} \text{C}$.
- July 8** Sample Pit "A-B". Record surface roughnesses of ice lenses, ice layers, snow surface. Radar spots in track-free zone.
- July 9** Continue sampling Pit "A-B". Perform two radar traverses.
- July 10** Tear down scientific equipment, pack. Warm and wet.
- July 11** Part of team leaves Dye-2.
- July 12** Continue tearing down camp. Remaining part of team leaves Dye-2.

Table I

Measurement Objectives

1. Measure backscatter coefficient at angles from 0 - 70 ° at three independent sites daily; perform calibrations at the start of each day.
2. Measure transmission loss by placing target sphere in a shallow cave that has at least a 1 m thick roof.
3. Conduct detailed measurements on surface (once every several days) and interface roughness (two locations) including careful characterization of the shape and extent of major ice lenses. Photograph pit walls.
4. Use dimethyl phthalate to collect thick section data on snow properties at various depths (especially near the top of ice lenses).
5. Record 10 m temperature.
6. Record 2 m temperature profile.
7. Record roughness of ice layer near 2 m depth (pit floor).
8. Complete a radar profile of the subsurface over an extended distance.
9. Document snow properties (density, grain sizes, etc.) in pits.

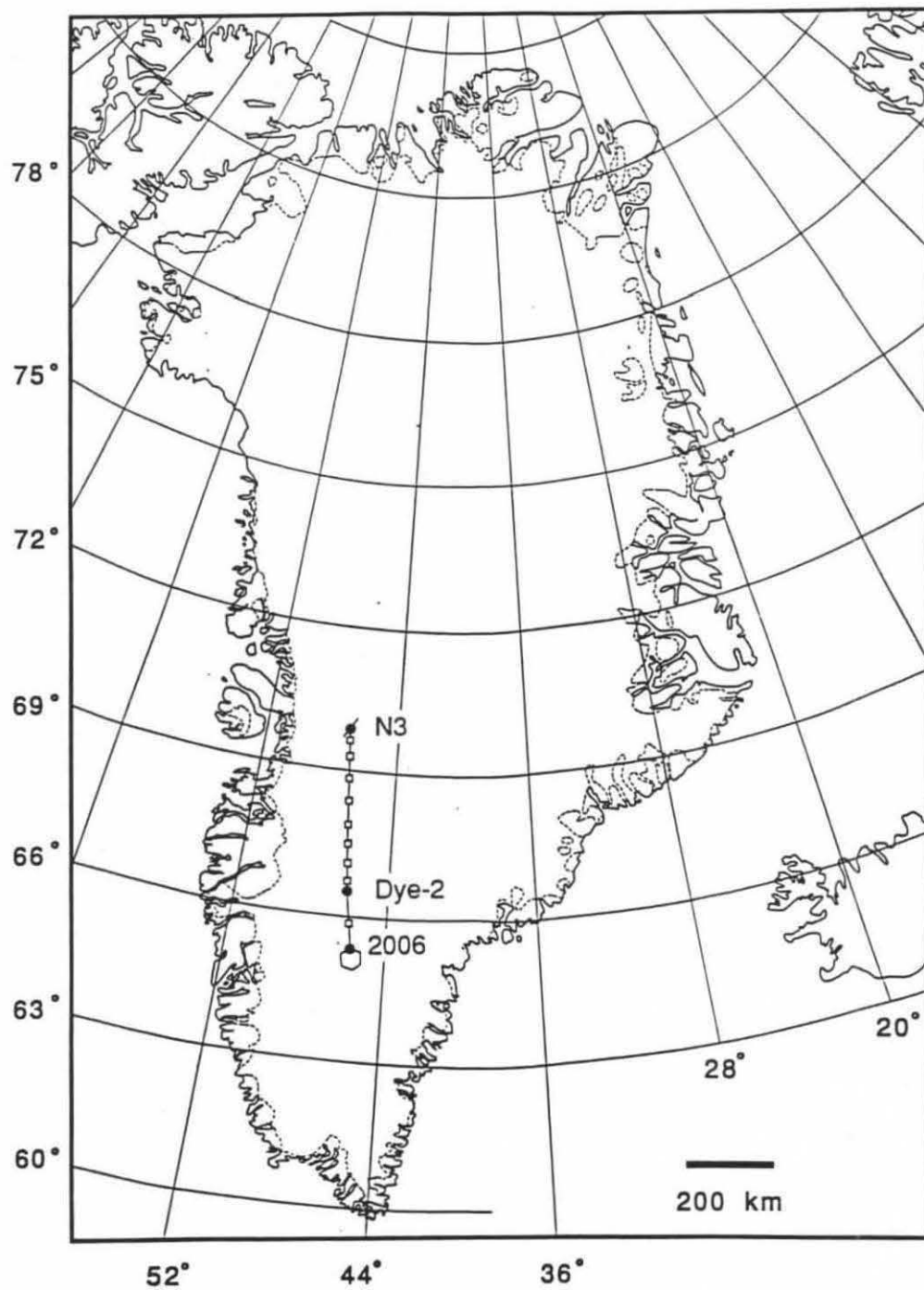


Figure 1: Map of Greenland, showing the traverse route with locations of pits along the route (open squares), Dye 2, and the strain hexagon at 65°N

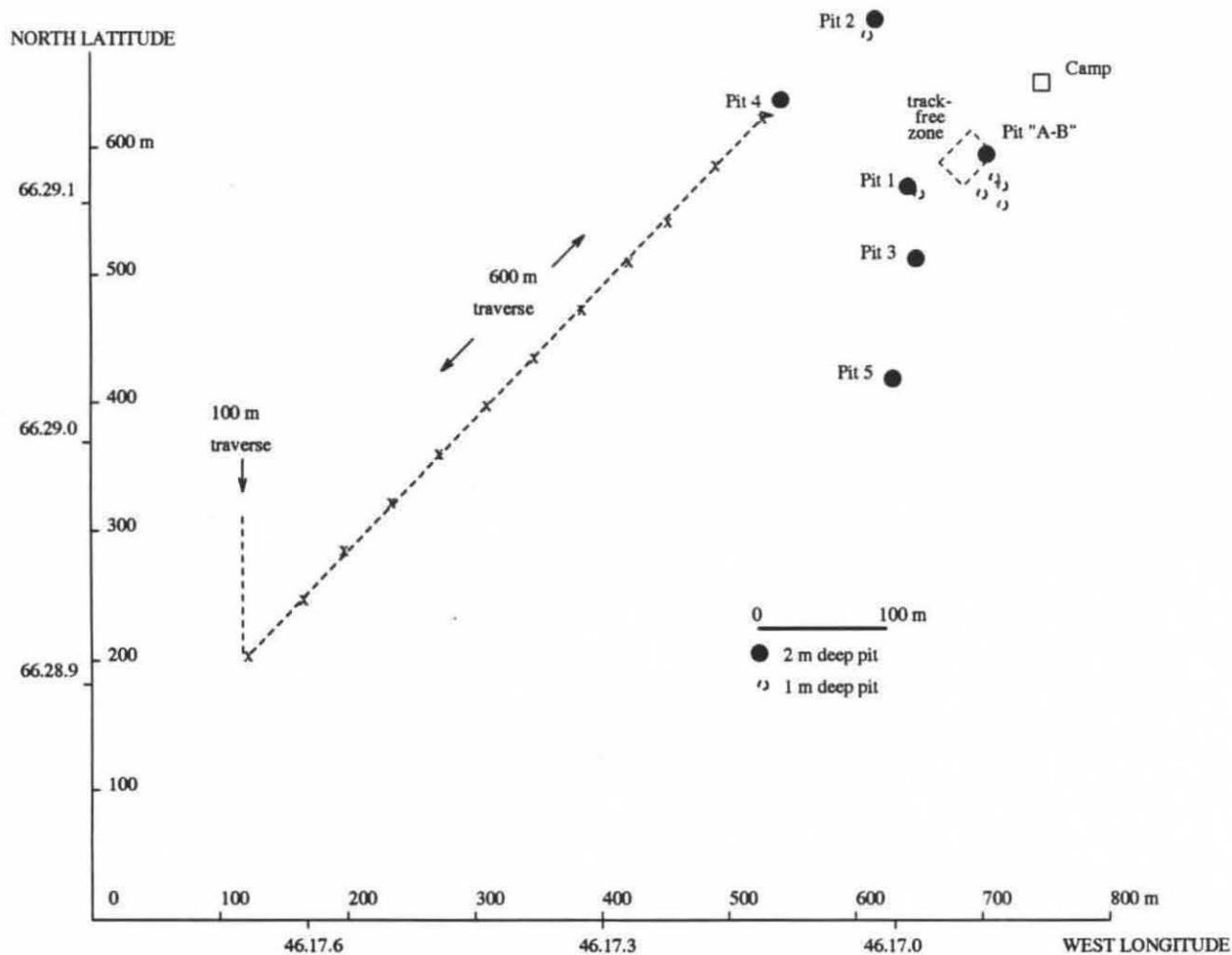


Figure 2: Map of experimental site at Dye 2, showing camp and pit locations, and routes of radar traverses

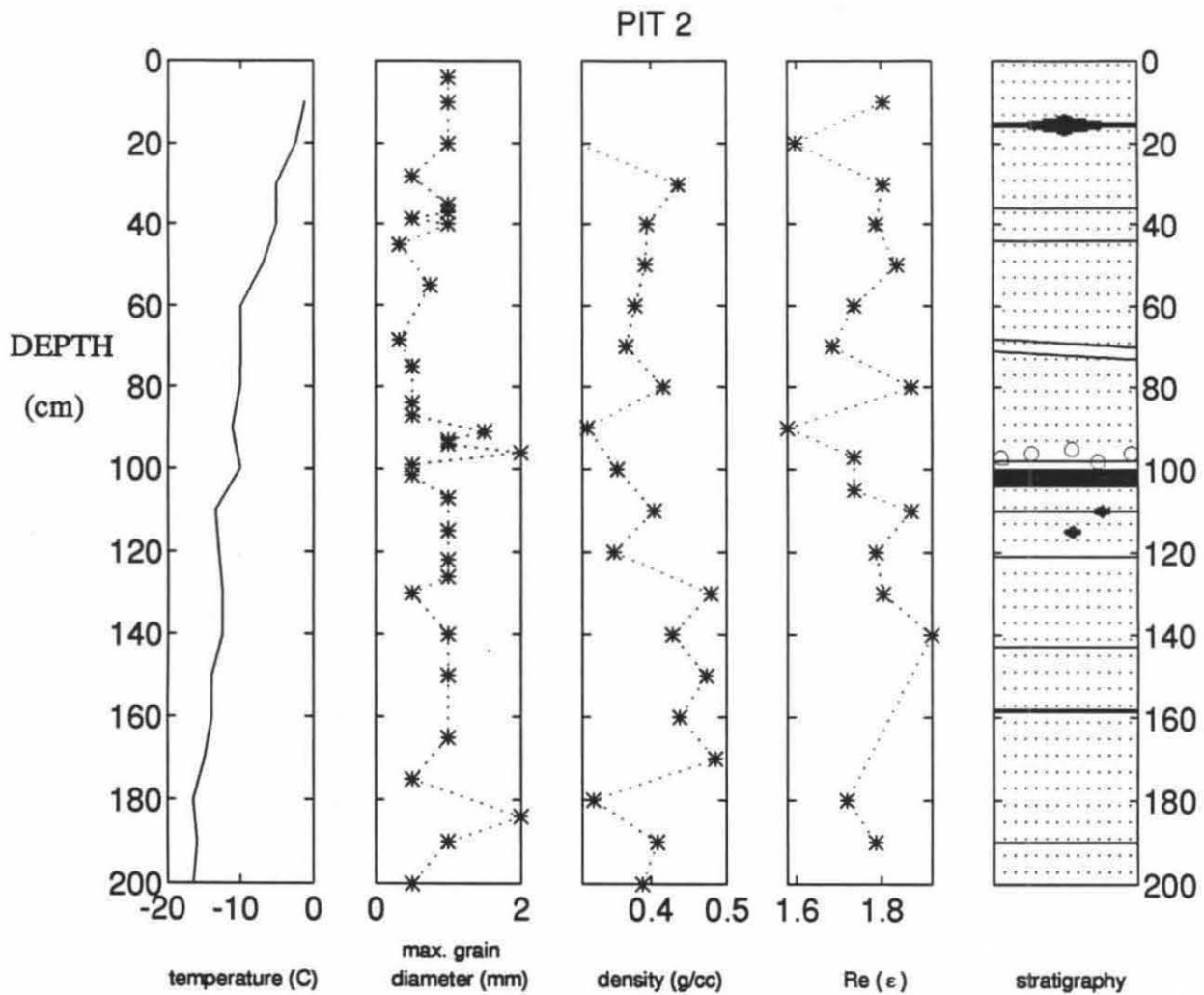


Figure 3: Snow properties sampled in Pit 2, as a function of depth: temperature, maximum grain size, density, real part of dielectric constant at 20 MHz, and stratigraphy. Black regions in the stratigraphy represent ice; dots represent snow; open circles represent large, fused ice grains.



Figure 4: One meter deep pit pit wall, showing variations in snow density and ice inclusions.



Figure 5: Radar set up.